Heat Vulnerability Index Methodology
Multnomah County Health Department
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Background

Extreme heat is the leading cause of weather-related mortality and exposure to extreme heat is expected to rise as an impact of climate change.[1] As record temperatures continue to be recorded across the globe, extreme heat events (EHE), or sustained periods of abnormally high temperatures, are increasing in frequency, intensity, and duration, thus creating a greater risk of heat-related illness and death.[2] While climate change is occurring at a global scale, the health impacts of extreme heat vary across geographies and populations, with vulnerability to heat-related morbidity and mortality being driven largely at the local level.[3]

In urban areas, intensive development, modification of natural surfaces, and daily human activity create urban heat islands (UHI) which amplify temperatures during extreme heat events.[4] Due to the impact of UHI, heat-related mortality rates in urban areas can be up to four times greater than that in nearby rural areas during extreme heat events.[5] However, temperatures vary substantially within cities, producing disproportionate heat-related health risks between geographic areas and the people who live, work, and play there. Heightened exposure to extreme heat tends to occur in disinvested neighborhoods with substandard housing which are primarily home to people with lower incomes and Black, Indigenous, and people of color (BIPOC) as a result of discriminatory housing and economic practices.[6]

Vulnerability to extreme heat can be understood as the interaction of sensitivity to heat and illness, degree of exposure to extreme heat, and capacity to adapt and mitigate harm. Analyzing heat vulnerability through this framework of sensitivity, exposure, and adaptive capacity can assess how vulnerability differs throughout a region and identify the people and places at greatest risk. Contextualizing vulnerability through these three domains can also identify areas for strategic intervention for mitigating heat-related health risks. Interventions to reduce heat vulnerability through reducing sensitivity or improving adaptive capacity could look to shorter-term solutions like emergency response and community-based adaptations like cooling centers and phone-based outreach and wellness checks. Interventions addressing exposure may instead prioritize longer-term heat mitigation strategies like increasing vegetation and tree canopy or reducing the density of heat absorbing materials in UHI.[7]

In Multnomah County, Oregon, the county which houses the city of Portland, extreme heat events are a substantial public health concern as they become more prevalent. In June 2021, areas in the Pacific Northwest in the United States and Canada experienced a heat dome, recording extremely high temperatures far beyond the range of historic observed temperatures in the region.[8] Within the Portland Metropolitan Region, daytime highs reached triple digits for three consecutive days with a peak temperature of 116ºF (NOAA, 2021). During this period, there were 78 reported heat-related deaths in Multnomah County.

In response to the growing threat of extreme heat in the region, our team from the Multnomah County Health Department's Environmental Health Services Program has constructed a heat vulnerability index to assess heat-related health concerns throughout the county and guide future heat mitigation strategies. Our index is constructed through the sensitivity, exposure, adaptive capacity framework and draws heavily on the methods used by Conlon et al (2020)[9] and Reid et al (2009)[10]. However, the indicators we selected for our index are based on current heat vulnerability literature and those which we know to be relevant to Multnomah County. This report describes our methods for indicator section, index construction, and initial validation efforts using heat-related deaths data from May through September of 2021 (which includes the time frame of the heat dome event).

Heat Vulnerability Framework

Sensitivity

Sensitivity to extreme heat refers to the physiological susceptibility to the harmful health impacts related to heat exposure and the body's ability to thermoregulate.[3] One of the most prevalent indicators of sensitivity within the literature is age, as heat stress has been shown to be especially harmful to both youth and older adults.[3,4,6,8,11] These age groups also tend to experience higher hospitalization and death rates during extreme heat events.[3] Living alone or being socially isolated can also increase sensitivity to extreme heat, especially for seniors, as seniors living alone may be unable to respond to an extreme heat event by themselves. [3,8,11] Another commonly used indicator of sensitivity to extreme heat is the presence of pre-existing conditions or comorbidities. Conditions such as diabetes, cardiovascular diseases, and respiratory diseases have been shown to contribute to complications in the body's physiological response to extreme heat thus heightening susceptibility to heat-related illness.[3,11]. Studies have also shown that men generally tend to be at higher risk than women to develop a heat-related illness during extreme heat events.[12]

Exposure

Exposure within our heat vulnerability framework assesses the degree of contact with extreme heat or variables shown to either increase or decrease local temperatures. Prolonged exposure to extreme heat produces thermoregulatory stress on the body and can lead to heat-related illness and mortality.[4] Exposure within an urban context focuses mainly on land cover and the structure of the built environment.[6] Areas experiencing higher ambient temperatures typically exhibit reduced vegetative cover, tree canopy, and soil moisture combined and a greater proportion of land area covered with impervious surfaces.[5] These artificial impervious surfaces absorb solar energy then radiate it back as heat, however, this can be mitigated by tree canopy and vegetative cover which provide shade and reflecting solar energy.[3] Population growth and density contributes to increased ambient temperatures through the heat generated by daily human activities.[4] Building and housing density also change the cooling potential of the built environment, since detached homes have more space for cooling where more dense areas, such as downtown districts, can further trap heat and absorb radiation.[5,6] Most heat-related deaths occur in the indoor home environment which exemplifies the importance of housing characteristics as indicators of exposure.[14] Metrics used to explore indoor heat exposure at the household-level, such as appliance and energy use, window placement, and access to air conditioning, can be difficult to collect; however, research suggests indoor temperatures are a function of outdoor conditions which are often more simple to measure.[1,14,15]

Adaptive Capacity

While sensitivity and exposure assess susceptibility to heat-related illness and how heat differs across a geography, adaptive capacity in our framework addresses what is needed to minimize both sensitivity and exposure and captures the existing barriers which hinder people from being able to do so. Adaptive capacity within this framework is therefore more focused on social and economic forces which reduce adaptive capacity to extreme heat at the population-level rather than assess the adaptive capacity of individuals. Educational attainment is one common measure of adaptive capacity to extreme heat and is closely associated with income. People with a high school education or less have been shown to experience higher heat-related death rates than people with greater levels of educational attainment and are more likely to live in neighborhoods with little tree canopy cover.[9,10] Like education, living in rental housing is another metric related to income and has been shown to reduce adaptive capacity to heat due to the availability of household amenities, access to air conditioning, and financial burden related to utilities costs.[3,6] Research also suggests that people with cognitive difficulties have less capacity to prepare for, evacuate their homes, and recover from extreme heat events and often have little access to transportation which acts as a barrier for evacuation and seeking refuge.[16] Similarly, people with limited English language proficiency have been shown to experience linguistic isolation and may be unable to understand extreme heat warnings if not provided in their preferred language, impacting protective behavior during extreme heat events.[6] Foreign-born populations, especially those with no documented citizenship, have been shown to experience social isolation, have difficulty obtaining protective resources to mitigate extreme heat, and experience reduced access to health care and insurance.[17]

There are also racial and ethnic disparities in adaptive capacity for extreme heat. Throughout the United States, environmental racism and discriminatory housing and economic policies have contributed to segregating BIPOC into disinvested neighborhoods which are disproportionately exposed to environmental hazards and have little access to protective factors, such as quality housing stock and air conditioning.[3,6,18] Within the Portland Metro Region, neighborhoods home to primarily BIPOC experience greater exposure to extreme heat and limited adaptive capacity, measured as access to air conditioning and public cooling centers, compared to primarily white neighborhoods.[15] Additionally, BIPOC tend to be underrepresented as stakeholders in climate-health discussions and decision-making processes and continue to be disenfranchised from large environmental movements, local efforts, and environmental groups.[19] This lack of representation in environmental decision-making results in limited political power and greater barriers to increasing adaptive capacity for extreme heat.

Heat Vulnerability Index Construction Methods

Indicator Selection

To construct our heat vulnerability index, we used the sensitivity, exposure, and adaptive capacity framework to create three domains and selected relevant indicators based on our review of the literature and data availability. We collected all of our data from existing sources and analyzed the data at the 2020 census tract level in Multnomah County. For data only available in raster format, we used zonal statistics to calculate mean values for each census tract. Once we obtained indicator values for each census tract in Multnomah County (n=197), percent values for tree and vegetative land cover were subtracted from 100 to capture non-tree and non-vegetative land cover so that higher values across all indicators would suggest greater vulnerability to extreme heat. Finally, we normalized our data to account for different units of measurement so that each indicator had a mean of zero and standard deviation of one.

HVI Indicators & Sources

Sensitivity		
Youth	Percent of the population under 18 years of age	ACS 2016-2020
Seniors	Percent of the population over 64 years of age	ACS 2016-2020
Seniors Living Alone	Percent of the population over 64 year of age, living alone	ACS 2016-2020
Male	Percent of the population that is male	ACS 2016-2020
CHD	Estimated crude prevalence of adults with coronary heart disease	CDC PLACES 2020
Diabetes	Estimated crude prevalence of adults with diabetes	CDC PLACES 2020
Physical Health	Estimated crude prevalence of adults with poor physical health for 14 days or more	CDC PLACES 2020
Exposure		
Population Density	People per square mile	ACS 2016-2020
Housing Density	Housing units per square mile	ACS 2016-2020
Tree Canopy	Percent of land area covered by tree canopy	Metro 2019 Tree Canopy LiDAR
Vegetation	Percent of land area covered by vegetation	NLCD 2019
Impervious Surfaces	Percent of land area covered by impervious surfaces	NLCD 2019
UHI	2016-2020 mean surface temperature	Metro LANDSAT 2016-2020
Adaptive Capacity		
Educational Attainment	Percent of the population with less than a Bachelor's degree	ACS 2016-2020
Rental Housing	Percent of the population living in rental housing	ACS 2016-2020
Cognitive Difficulty	Percent of adults with a cognitive disability	ACS 2016-2020
Foreign-Born Population	Percent of the population born outside of the United States	ACS 2016-2020
English Language Proficiency	Percent of the population speaking English "less than very well"	ACS 2016-2020
Race/Ethnicity	Percent of the population that identifies as Black, Indigenous, or person of color	ACS 2016-2020

Principal Component Analysis

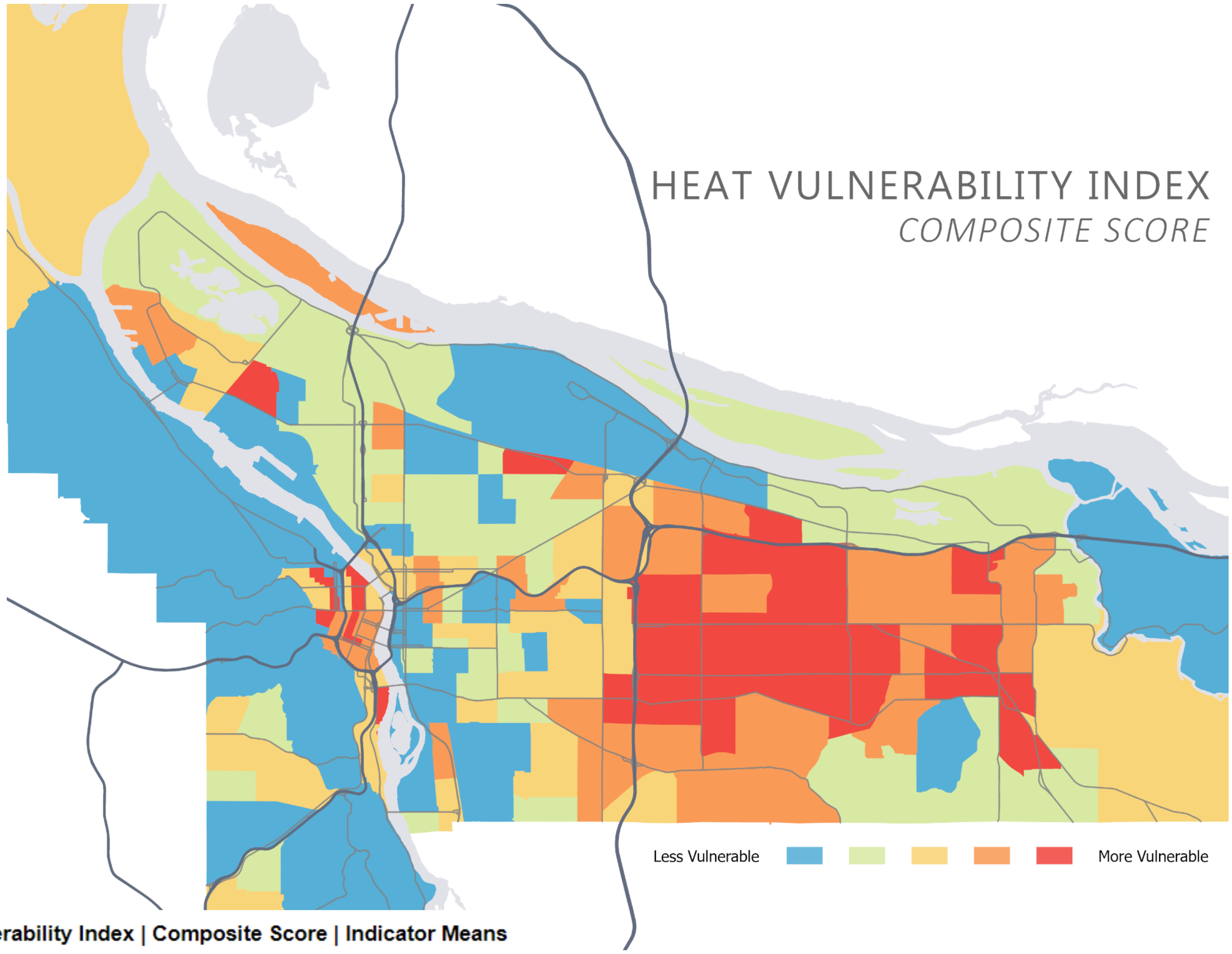
One of the more common techniques for constructing a heat vulnerability index is principal component analysis (PCA).[9,10,20,21] PCA is a dimension-reduction technique which takes potentially correlated variables and outputs independent factors.[9,10] Using this method allows a dataset to be narrowed down to the factors which account for most of the variation. For our heat vulnerability index, we conducted an unsupervised PCA using independent variables which we selected based on theory and associations with heat-related illness in prior literature. Our analysis was conducted in Rstudio using the function *prcomp()*. PCAs were conducted for each of our three domains corresponding to our sensitivity, exposure, and adaptive capacity framework. For each domain PCA, factor loadings with eigenvalues (measurement of variance in the data) greater than 1 were retained and rotated using the varimax rotation function *varimax()* which helps to make factors from the PCA more statistically independent from the original dataset.[10] Factors in each domain PCA were summed for each census tract to calculate corresponding domain scores and domain scores were summed for a composite heat vulnerability score.

Following the index construction methods of Conlon et al. (2020)[9], we also conducted a supervised PCA. In contrast to our unsupervised PCA, the indicators for the supervised PCA were chosen based on their correlation with heat-related illness data. To identify variables for our supervised PCA, we regressed hospital visits for heat-related illness from May-September of 2020-2022 with each individual indicator used in our unsupervised PCA and selected indicators with the strongest associations to heat-related illness. Heat-related illness hospitalization data was only available at the zip code level and were apportioned to census tracts based on tract population as a proportion of zip code population. With the indicators that were moderately significantly associated ($p<0.20$) with heat-related illness, we conducted PCAs for each domain. The variables removed from index construction in this process were percent of the population that is male, percent of the population under the age of 18, percent of the population over the age of 64, and average annual surface temperature. This resulted in a reduced number of factors in the sensitivity domain, creating a composite score that appeared to overrepresent the exposure domain. However, the differences between our supervised and unsupervised composite heat vulnerability index (HVI) scores were minimal, leading us to select the index constructed using the unsupervised PCA methods as it is difficult to justify removing four important indicators from index construction and any assumptions introduced into the model in an attempt to bridge hospitalization data across geographies.

Additionally, we constructed a composite index score using an unsupervised PCA for all indicators rather than summing domain scores. Many of the heat vulnerability indices that we reviewed use this method and assign domains to individual PCA factor loadings based on which variables account for the largest degree of variance. While the composite HVI scores from this method and those from summing domains scores were similar once visualized, we opted to use our original method of calculating composite scores as sum of domain scores. This method is best suited for guiding intervention approaches because after identifying locations where people experience high vulnerability to heat, vulnerability can be disaggregated into its sensitivity, exposure, and adaptive capacity components, highlighting areas where domain-specific interventions can make the most substantial reductions in overall heat vulnerability.

Heat Vulnerability Visualization

Composite Heat Vulnerability Score

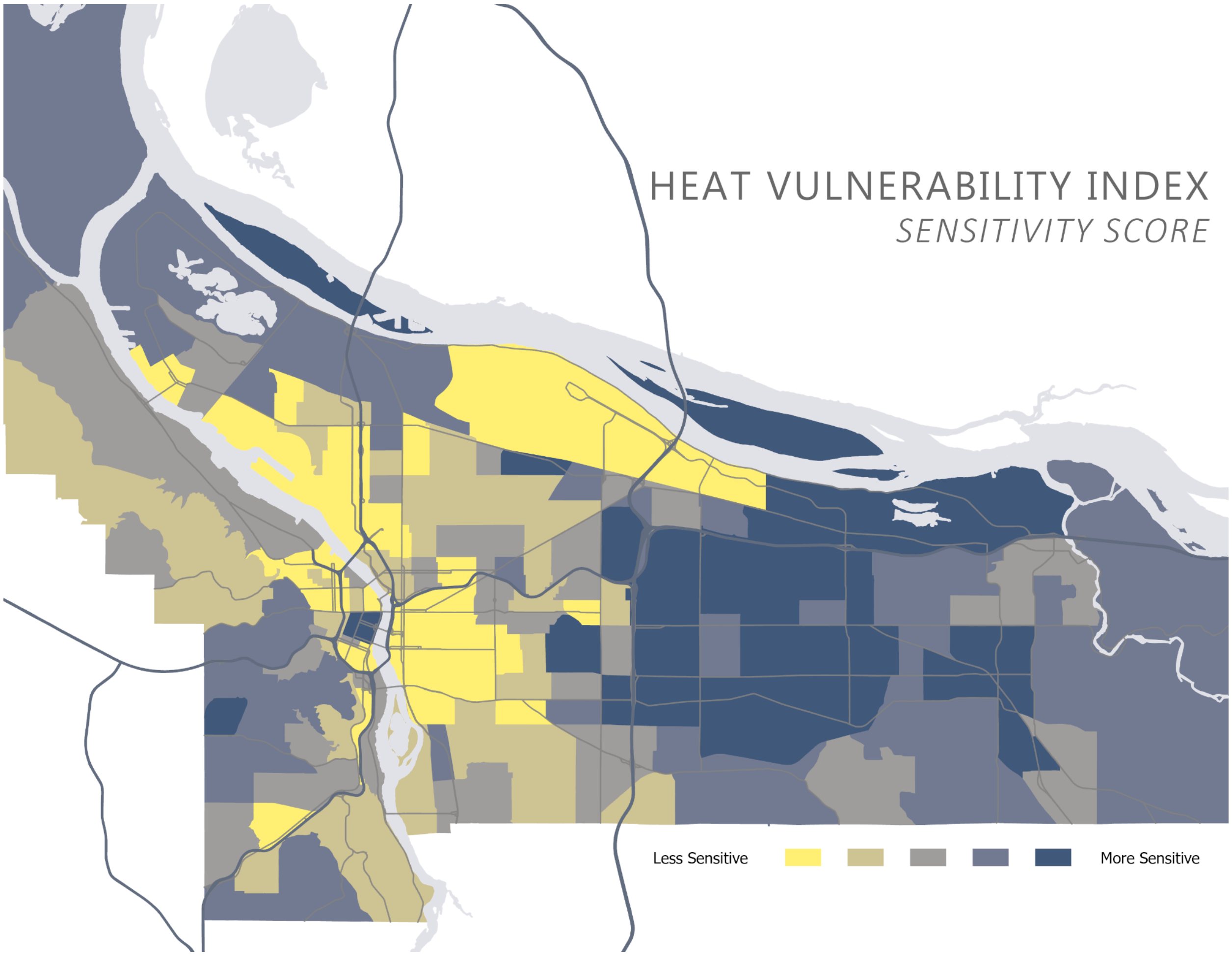


Heat Vulnerability Index | Composite Score | Indicator Means

	Most Vulnerable	Least Vulnerable	Multnomah County
Youth	19.9%	15.8%	17.4%
Seniors	16.0%	13.1%	13.6%
Seniors Living Alone	33.5%	22.9%	32.7%
Male	48.1%	49.6%	49.5%
CHD	5.8%	3.8%	4.5%
Diabetes	8.9%	5.8%	7.0%
Physical Health	14.5%	9.2%	11.2%
Population Density	12,247	5,603	8,708
Housing Density	6,304	2,401	4,072
Non-Tree Canopy	80.1%	63.6%	73.8%
Non-Vegetation	95.5%	75.6%	87.5%
Impervious Surfaces	61.3%	44.1%	53.8%
Surface Temperature (F)	84.5	82.1	83.7
Less than BS Education	70.0%	34.2%	51.8%
Rental Housing	52.0%	28.4%	41.0%
Cognitive Difficulty	7.8%	6.2%	6.2%
Foreign-Born Population	23.0%	8.2%	13.0%
English Language Proficiency	6.3%	0.5%	2.7%
Race/Ethnicity	42.2%	19.7%	29.5%

Within Multnomah County, 39 census tracts (19.8%) made up the top quintile of heat vulnerability. Of these 39 tracts, 29 (74%) are located east of the I-205 and largely clustered in East Portland. Parts of Downtown Portland and two areas in North Portland, around the Portsmouth and Cully neighborhoods, are also in the top quintile for heat vulnerability.

Sensitivity

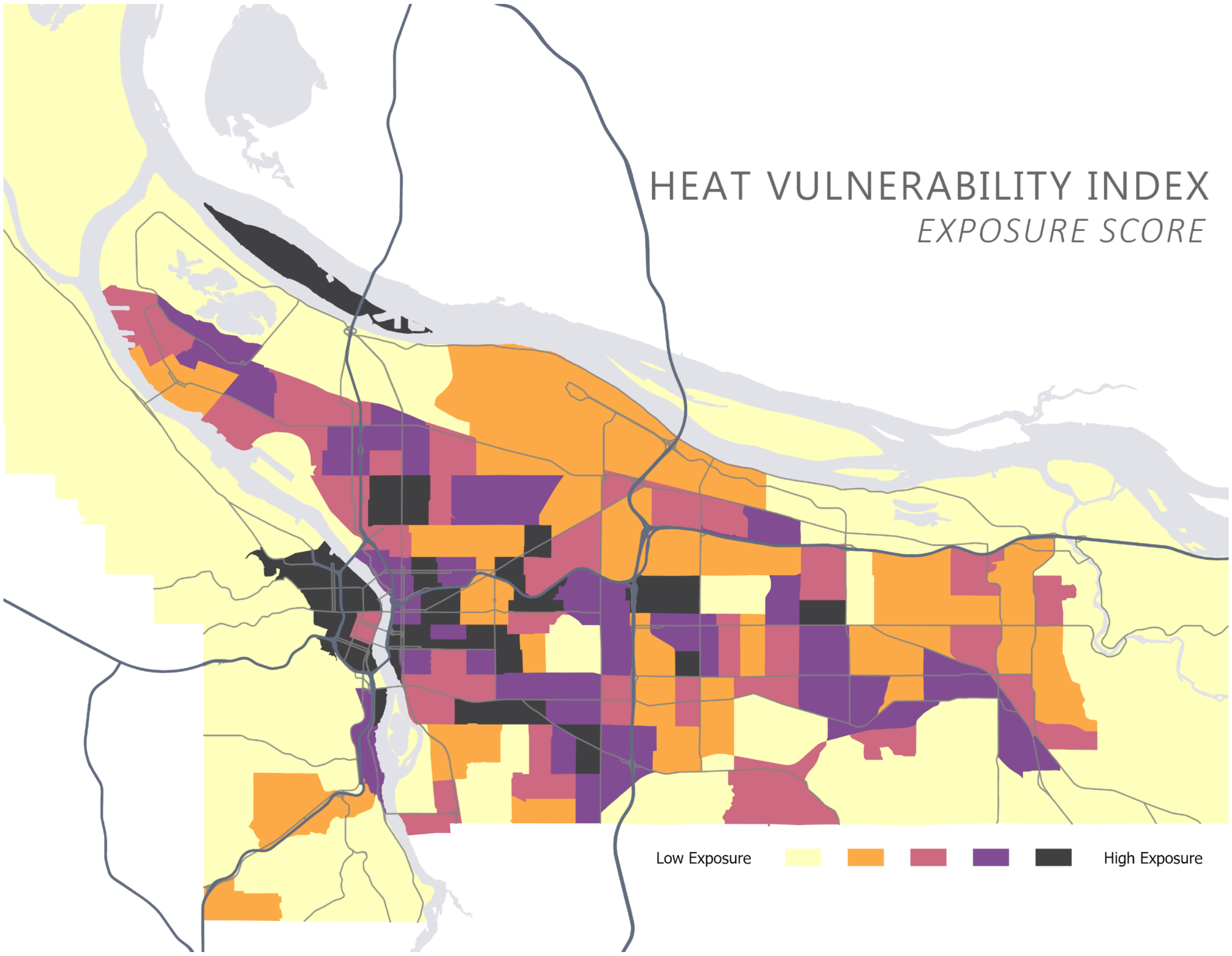


Like the composite score, sensitivity to extreme heat in Multnomah County is highly concentrated in East Portland, with 35 of the 39 tracts (89.7%) in the top quintile for heat sensitivity falling near or east of 82nd Avenue and the I-205. These areas appear to have substantially higher youth and senior populations and a greater prevalence of chronic disease. While there are more seniors living in the areas with the highest sensitivity scores, less seniors live alone compared to the least sensitive areas and county. Additionally, highly sensitive areas appear to have a smaller male population than both the county and the least sensitive areas.

Heat Vulnerability Index | Sensitivity | Indicator Means

	Most Sensitive	Least Sensitive	Multnomah County
Youth	21.3%	9.5%	17.4%
Seniors	16.0%	8.9%	13.6%
Seniors Living Alone	32.4%	36.2%	32.7%
Male	48.1%	50.1%	49.5%
CHD	6.3%	3.1%	4.5%
Diabetes	9.6%	5.0%	7.0%
Physical Health	15.2%	8.9%	11.2%

Exposure

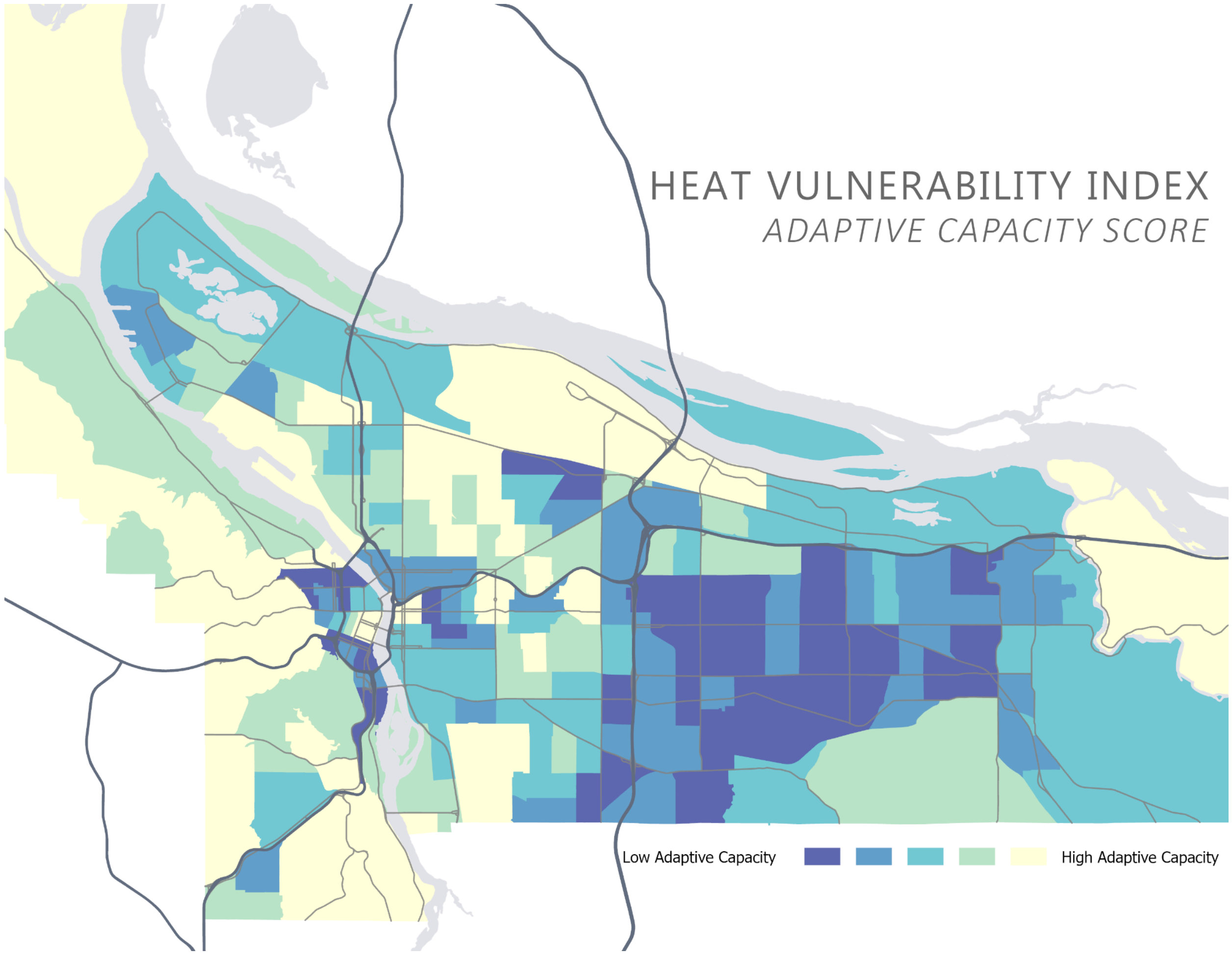


Unlike sensitivity, areas in Multnomah County with higher exposure to extreme heat are located around Downtown Portland and the inner Eastside of the city, accounting for 33 of the 39 tracts (84.6%) within the highest quintile of heat exposure. These areas tend to be densely populated, highly developed, and exhibit little vegetation and tree canopy coverage. The tracts with the highest exposure score also experience temperatures that are nearly 5F hotter than areas with the least exposure.

Heat Vulnerability Index | Exposure | Indicator Means

	Most Exposed	Least Exposed	Multnomah County
Population Density	16,180	3,976	8,708
Housing Density	9,375	1,566	4,072
Non-Tree Canopy	80.8%	57.8%	73.8%
Non-Vegetation	98.1%	59.8%	87.5%
Impervious Surfaces	69.7%	29.8%	53.8%
Surface Temp (F)	85.0	80.4	83.7

Adaptive Capacity



Adaptive capacity for extreme heat in Multnomah County more closely resembles sensitivity with areas showing lower adaptive capacity located primarily in East Portland and scattered near Downtown Portland. A larger share of the populations living in these areas appear to be BIPOC, born outside of the United States, and have limited English proficiency than the highest capacity tracts and county average. Additionally, more people in the tracts experiencing the lowest degree of adaptive capacity have less than a Bachelor's degree education and live in rental housing.

Heat Vulnerability Index | Adaptive Capacity | Indicator Means

	Lowest Capacity	Highest Capacity	Multnomah County
Less than Bachelor's Degree Education	64.3%	35.8%	51.8%
Rental Housing	55.5%	23.6%	41.0%
Cognitive Difficulty	5.7%	6.9%	6.2%
Foreign-Born Population	23.4%	7.1%	13.0%
Limited English Proficiency	6.4%	0.5%	2.7%
Race/Ethnicity	40.3%	20.2%	29.5%

While cognitive difficulty was identified in the literature as a factor contributing to reduced adaptive capacity to extreme heat, tracts with the highest degree of adaptive capacity have a larger share of people with cognitive difficulties than both the lowest capacity tracts and the county average.

Index Validation, Limitations & Intended Uses

2021 Heat Dome Event & Heat-Related Deaths

To test the ability of our heat vulnerability index to capture how the burden of heat-related health concerns are distributed throughout Multnomah County, we analyzed the distribution of heat-related deaths data from May through September of 2021 in Multnomah County in relation to our composite heat vulnerability index scores. Heat-related death data was obtained from Oregon Health Authority vital records with cause of death defined as exposure to excess natural heat or deaths with effect of heat and light as underlying cause. Deaths in which exposure to heat of human-made origin as a cause were excluded. Deaths were geocoded by the Oregon Health Authority and all personally identifying information was removed. The heat-related deaths data we used for this analysis are primarily residential, as 94% of the deaths identified occurred in the decedent's personal residence.

Of the 72 heat-related deaths identified during this period, 23 (32%) occurred in the census tracts making up the top quintile for heat vulnerability. 40 of the 72 deaths (56%) occurred within the top two quintiles for heat vulnerability. The number of deaths increased to 47 (65%) within 200 meters of tracts making up the top two quintiles for heat vulnerability. Compared to tracts showing lower heat vulnerability scores, 7 (10%) of total deaths occurred in the bottom quintile, 18 (25%) in the bottom two quintiles, and 26 (36%) within 200 meters of the bottom two quintiles for heat vulnerability. While our index does not provide a perfect depiction of the distribution of individual heat-related outcomes, it is able to capture spatial, population-level trends related to heat-related deaths in Multnomah County.

Spatial Discrepancies in Heat Vulnerability

Our analysis of heat vulnerability throughout the county reveals areas where high vulnerability tracts are adjacent to low vulnerability tracts. Vulnerability, as constructed in our analysis, does not act as a gradient when visualized. The indicators included in our HVI are summarized at the census tract level and each contribute to a tract's composite vulnerability score. Therefore, tracts with few residents have low values for the indicators in the sensitivity and adaptive capacity domains, since these indicators are demographic-based, and thus display low vulnerability scores. Tracts with larger populations that are adjacent to these areas may then show heightened heat vulnerability scores comparatively. This relationship can further impact heat vulnerability in areas adjacent to low population tracts as vacancy has been identified as a risk factor for heat-related illness.[6] In other cases with adjacent high and low heat vulnerability tracts, features of the natural and built environments may contribute to these differences such as large parks reducing heat and increasing vegetative and tree canopy cover or large highways and coinciding infrastructure increasing imperviousness and segregating populations.

Limitations

Like all population health indices, our HVI comes with limitations. Construction of our HVI is based on existing large-scale estimates which come with their own biases and errors introduced by how they were modeled and by whom. Summarizing our data at the census tract level also introduces possible modified areal unit issues and attempting to use this aggregated population-level data in our index to predict measured health outcomes could result in ecological fallacies. These data may not fully represent places and people or how heat and health are experienced throughout the county; however, these data expose potential trends that are worth exploring to enhance our understanding of extreme heat and future intervention approaches. Due to these same limitations and our further modification of the data through our unsupervised PCA methods, our HVI should be viewed as a tool to enhance extreme heat responses once contextualized by public input. Additionally, our index utilizes surface temperature measurements as an important metric of heat exposure which may not fully capture how heat differs throughout the county and how it is experienced. Research suggests that air temperature is a stronger indicator of heat-related health [22] and our use of surface temperature was due to the availability of the data. As air temperature measures become available, we plan to reconstruct our HVI and analyze how heat exposure and vulnerability change throughout the county as a result. Finally, PCAs are highly sensitive to the indicators selected and domain and composite scores can therefore vary depending on the variables analyzed. However, the variables included in our index were selected based on their scientifically-based relationship with heat-related illness and mortality. While different operationalizations of these variables could alter our HVI scores, we are confident that the current indicators included in our analysis help to contextualize heat-related health in Multnomah County and guide future intervention approaches.

Intended Uses

This heat vulnerability index provides a general overview of the factors relating to population-level risk of heat-related illness and how it is distributed throughout Multnomah County. Our framework for this index views heat vulnerability as a product of the interactions between sensitivity, exposure, and adaptive capacity which helps to identify pathways for interventions to reduce heat vulnerability. This tool can identify areas at a higher risk of heat-related illness and reference the three domains to identify where efforts are needed most. Our heat vulnerability index is based on large-scale estimates and is therefore not without limitations and scores generated through use of PCA are highly sensitive to the indicators used in the analysis. Therefore, this index is best used as a resource to explore trends, enhance mitigation efforts, and identify areas where outreach and engagement can provide a more accurate representation of extreme heat and the people experiencing a disproportionate burden of heat-related illness in Multnomah County.

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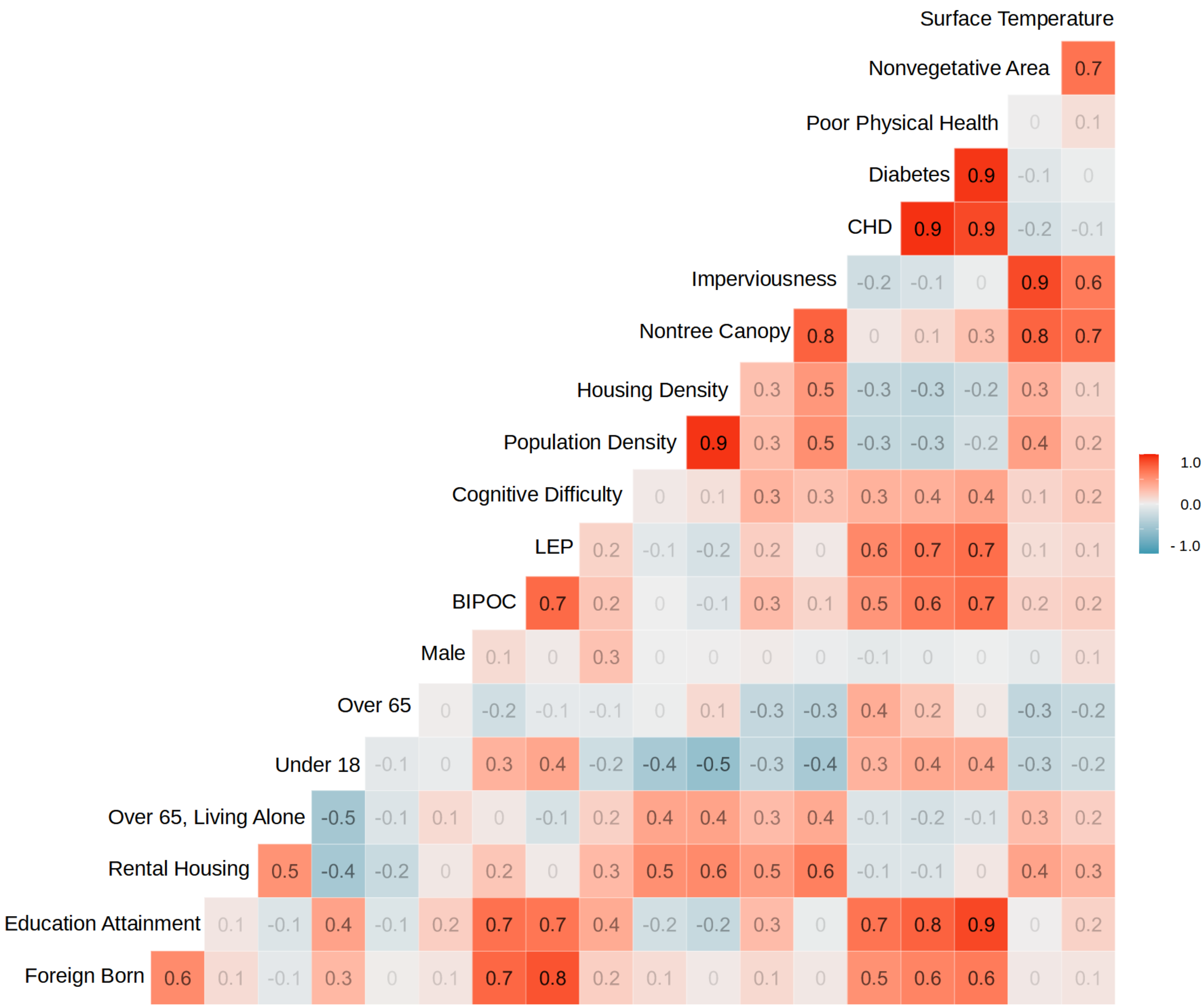
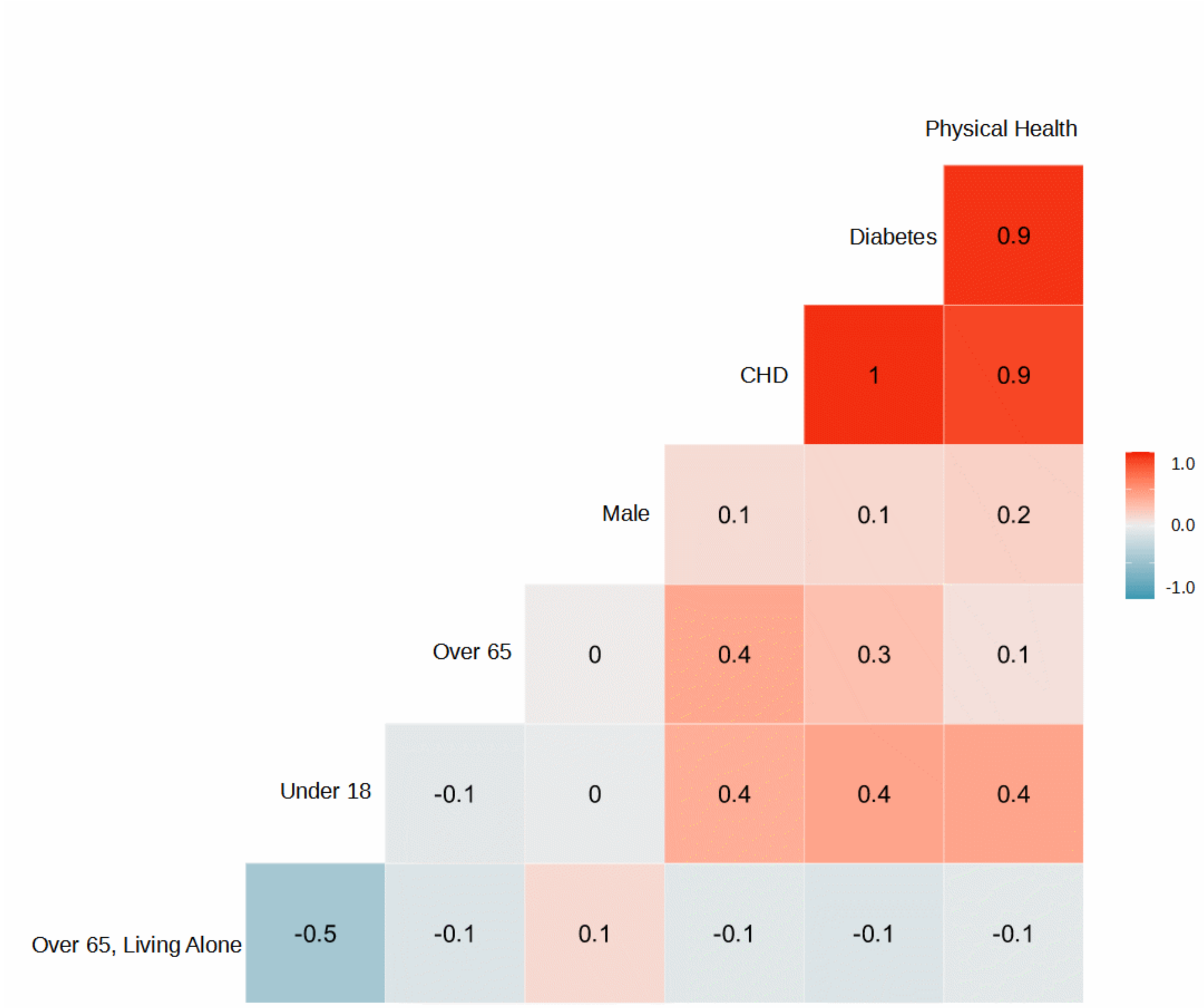
Appendix

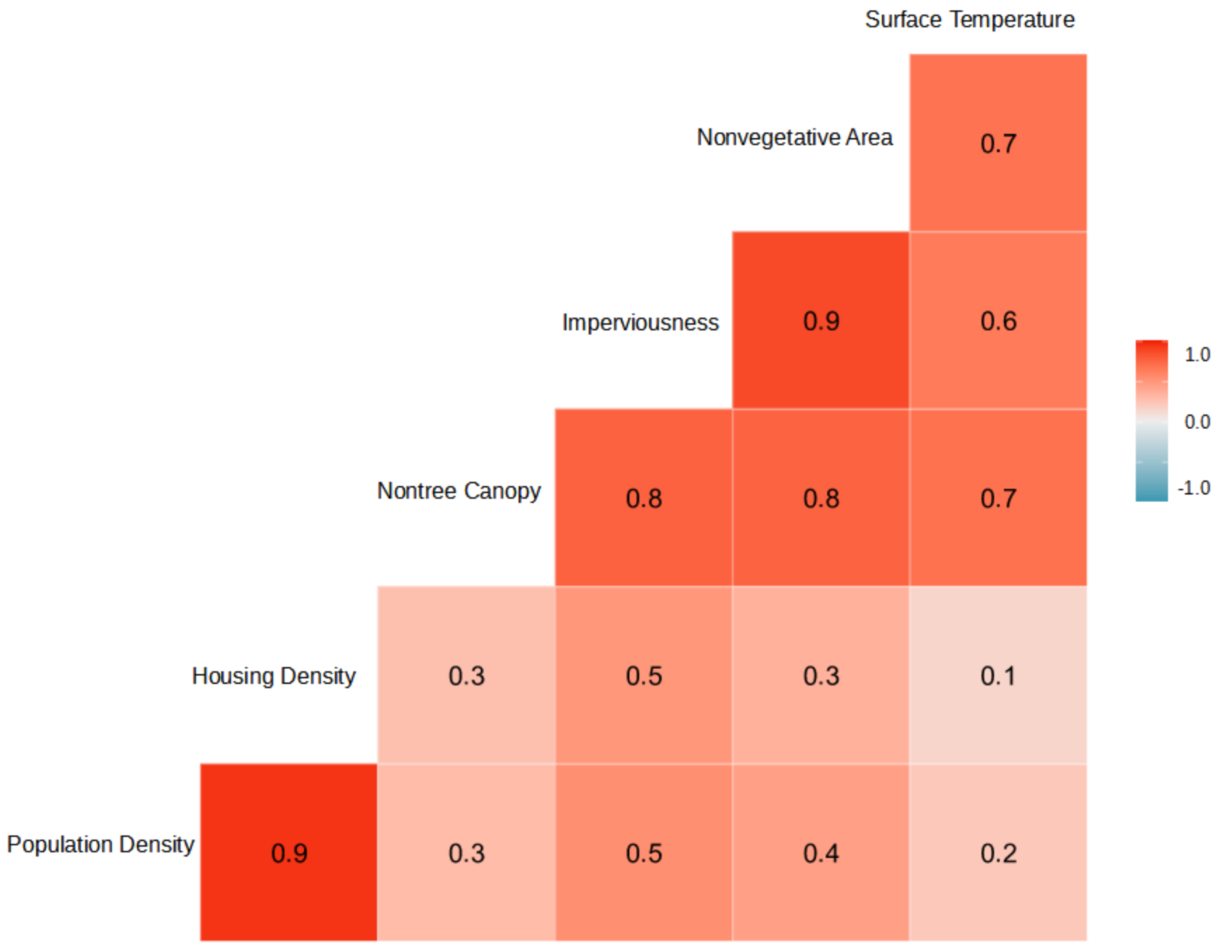
Correlation | All Indicators



Correlation | Sensitivity



Correlation | Exposure



Correlation | Adaptive Capacity